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Long-term current observations are made in the Korea Strait for the first time. Eleven bottom-mounted acoustic Doppler current profilers returned high quality current profile measurements along two lines, west and east of Tsushima Island for nearly a year. a high velocity current core was found to exist on the western slope of the strait west of Tsushima Island for the entire recording period. Tsushima Island disrupted the current flow towards the northeast to such an extent that a counter currently commonly existed in the island shadow. Currents with tides flowing towards the northeast along the strait exceeding 120 cm/s while non-tidal currents were found to range over 45 cm/s.

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Current and Tide Observations in the Korea Strait

W.J. Teague, G.A. Jacobs, H.P. Perkins, J.W. Book, P.J. Hogan, J.M Dastugue

Long-term current observations are made in the Korea Strait for the first time. Eleven bottom-mounted acoustic Doppler current profilers returned high quality current profile measurements along two lines, west and east of Tsushima Island for nearly a year. A high velocity current core was found to exist on the western slope of the strait west of Tsushima Island for the entire recording period. Tsushima Island disrupted the current flow towards the northeast to such an extent that a counter current commonly existed in the island shadow. Currents with tides flowing towards the northeast along the strait exceeded 120 cm/s while non-tidal currents were found to range over 45 cm/s.

CURRENTS	TRANSPORTS	TIDES	INERTIAL CURRENTS	RELATED PAPERS

This work was sponsored by the Office of Naval Research (program element PE0601153N) as part of the following basic research projects: "Yellow and East China Seas Response to Winds and Currents" (YES), "Linkages of Asian Marginal Seas" (LINKS), and Japan/East Sea Program (JES).

If you have any questions or comments please contact:
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CURRENTS

Results are shown from continuous current measurements across Korea-Tsushima Strait between May and October 1999. The data are from eleven bottom-mounted Acoustic Doppler Current Profilers with pressure gauges. These recorded full-depth profiles of currents along two lines, one at each end of the Strait. The two sections show markedly different mean flow regimes. At the southern entrance, the cross-section flow varies smoothly across the channel, showing a broad maximum at mid-channel. The northern section, is marked by strong spatial variability, but in the mean consists of two streams, one on each side of the strait. Between the two is a regime of highly variable flow with a weak mean, presumably the wake from Tsushima Island. Flow variability in time is described by statistical measures and by snapshots of representative situations.

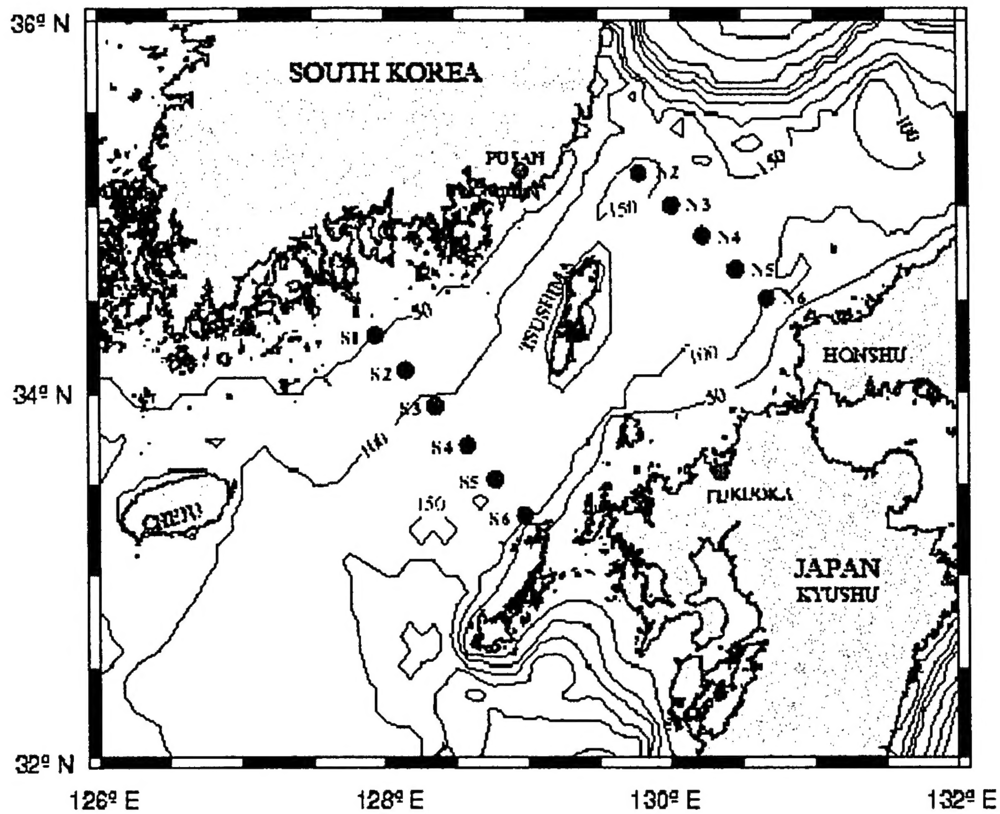
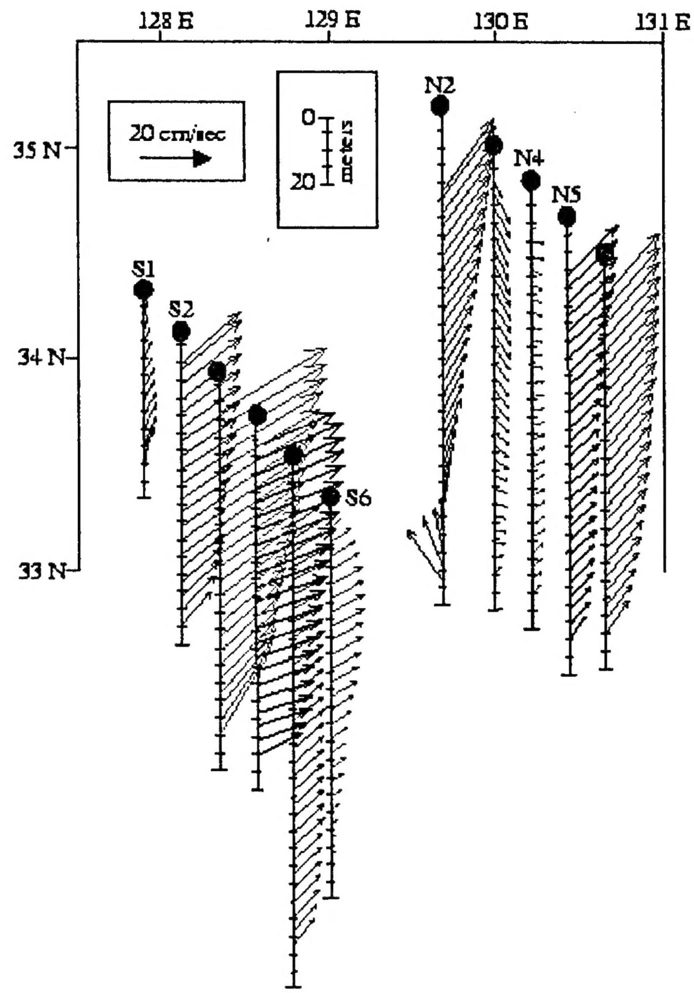


Figure 1. Mooring locations and bathymetry.

Figure 2. Time-averaged velocity vectors for all sites and all depths. Mooring locations are marked by a red circle referenced to the geographical coordinates. A vertical line extending downward from the symbol denotes depth from surface to bottom. Individual vectors are drawn in plan view, as though the surface of the page were a horizontal plane, with the vector originating from its respective depth on the vertical line. Thus, the uppermost current vector at site N2 is at about 25 m depth and directed towards the northeast.



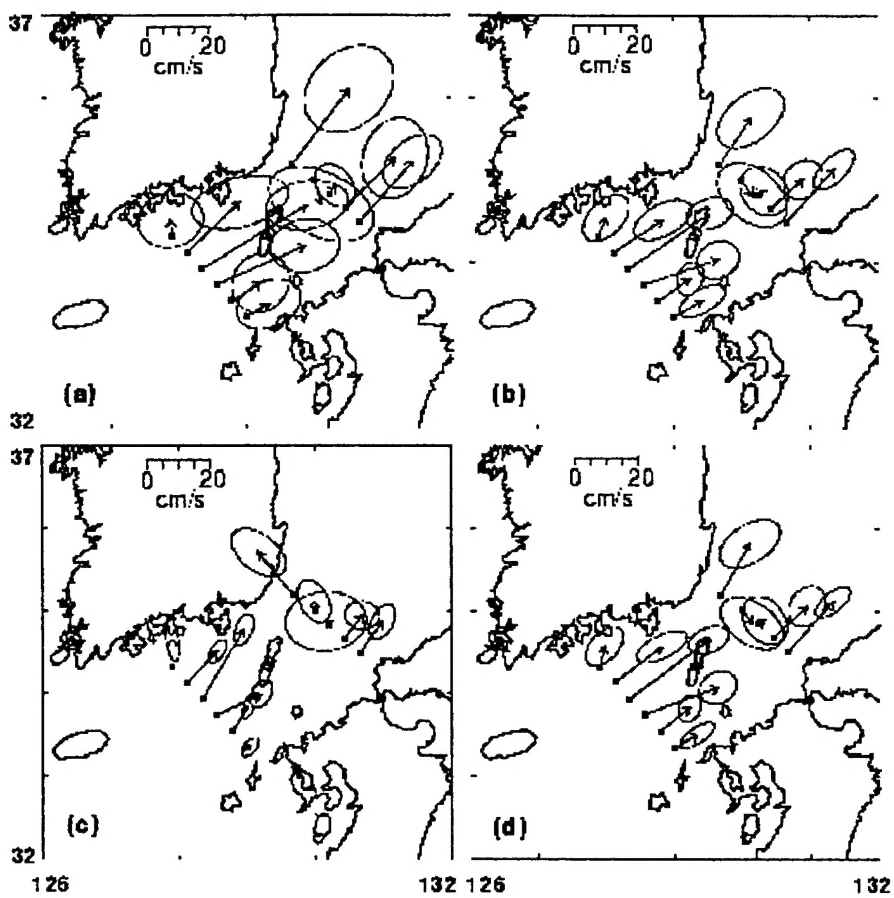
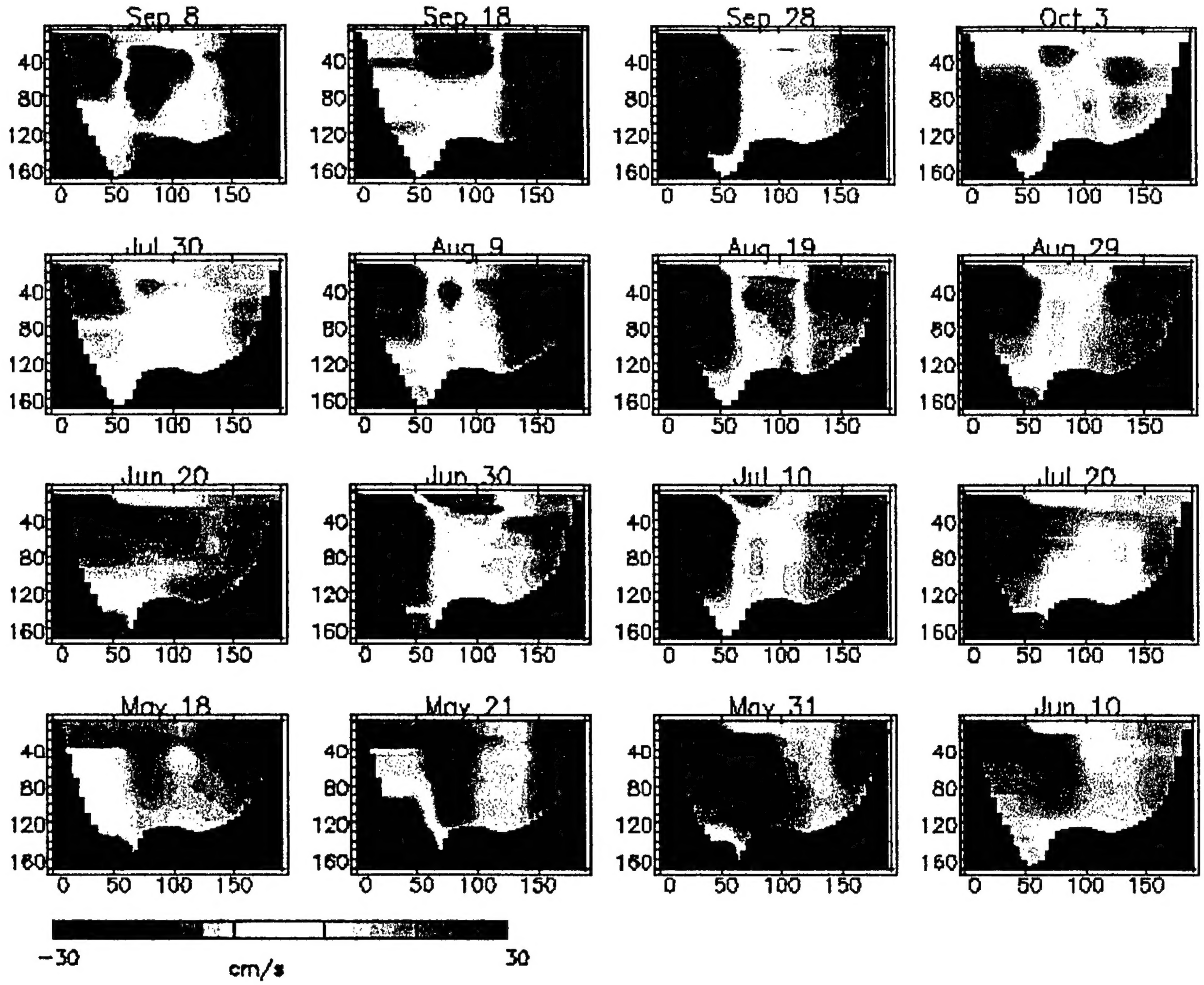


Figure 3. Mean current vectors: (a) near the surface (shallowest ADCP depth bin), (b) at mid-depth (middle bin), (c) near the bottom (deepest bin), and (d) depth-averaged. Means and devitions are based on de-tided currents over the May - October observing period.


Sep 8
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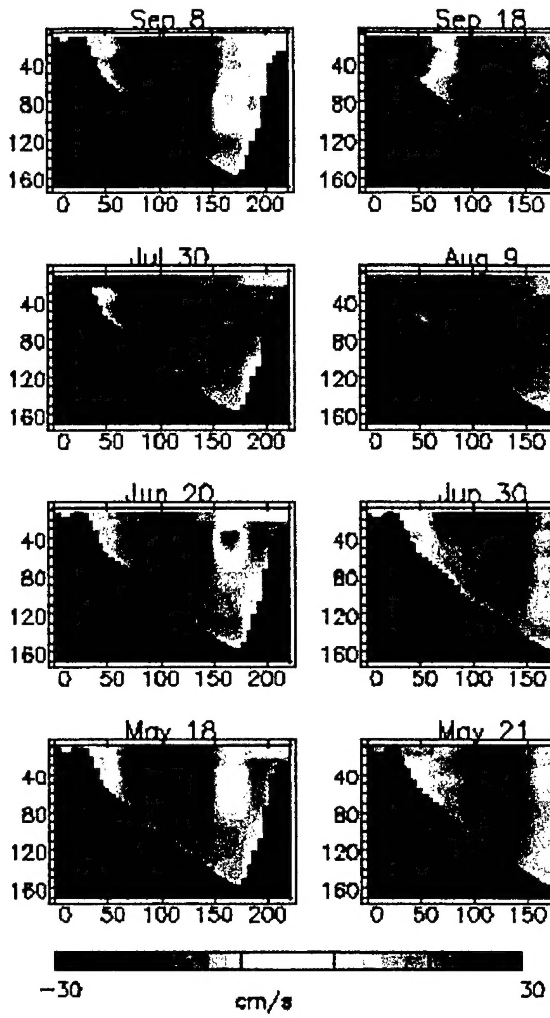
cm/s
30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Jun 10
40
80
120
160
0 50 100 150 200
-30
cm/s
30

Mooring	Lat	Lon	Start Day	End Day	Top Bin	Bottom Bin	Bin Size	Water Depth
S1	34.32	127.90	130	289	5	53	2	59
S2	34.13	128.12	129	289	7	83	2	89
S3	33.93	128.34	129	288	11	103	4	113
S4	33.74	128.56	128	287	9	97	4	107
S5	33.54	128.78	128	287	19	143	4	152
S6	33.35	129.00	128	286	9	105	4	115
N2	35.20	129.67	125	282	25	137	2	142
N3	35.01	129.99	126	283	13	125	4	132
N4	34.84	130.21	126	283	13	117	4	127
N5	34.67	130.43	127	284	16	120	4	130
N6	34.50	130.65	127	284	12	108	4	118

Table 1. ADCP Summary. Bin sizes and water depths are in m.

ADCP	$\overline{Vr}$	σ_{Vr}	Vr_{min}	Vr_{max}	$Vrtot_{min}$	$Vrtot_{max}$
S1	5.41	7.17	-25.65	31.96	-93.63	122.77
S2	17.80	7.98	-18.54	34.63	-71.20	125.62
S3	29.52	6.09	12.55	48.14	-53.11	123.38
S4	21.45	5.79	8.62	46.87	-73.72	123.15
S5	11.19	4.33	-2.45	24.38	-71.26	92.35
S6	7.26	6.06	-7.24	28.06	-85.66	97.46
N2	17.46	9.85	-6.64	52.37	-84.70	130.66
N3	-1.25	6.33	-18.49	20.21	-97.46	95.62
N4	2.23	6.05	-19.66	19.08	-84.61	73.20
N5	14.01	6.59	-2.29	35.61	-60.44	116.63
N6	20.42	6.14	2.53	35.80	-68.90	105.97

Table 2. Statistics for the velocity component normal to the section in cm/s. Mean velocity ($\overline{Vr}$), standard deviation ($\sigma_V r$), minimum velocity observed (Vr_{min}), and maximum velocity observed (Vr_{max}) are for the vertically averaged currents after tide removal. $Vrtot_{min}$ and $Vrtot_{max}$ are the minimum and maximum currents observed without removing tides or depth averaging.

TRANSPORTS

Transport variations through the Korea-Tsushima Strait are examined. An optimal interpolation (OI) scheme is used to interpolate the data spatially and to provide error estimates along each section. The strong northeastward current core through the southern section lies approximately in the center of the strait, and small southwestward flows occur sporadically near both the Korea and Japan coasts. Much of the flow through the northern line occurs near the Korea and Japan coasts with a weak southwestward mean flow and large variability in the strait center on the lee side of the Tsushima Island. The estimated mean transport is 2.8 Sverdrups (Sv) through the southern line and 2.4 Sv through the northern line. However, the northern line does not extend close to the Korea coast where there is significant flow. Expected errors in the transport estimates at any time are about 0.5 Sv RMS for each mooring line.

Mean Transport
Transport Time Series

Plate 4

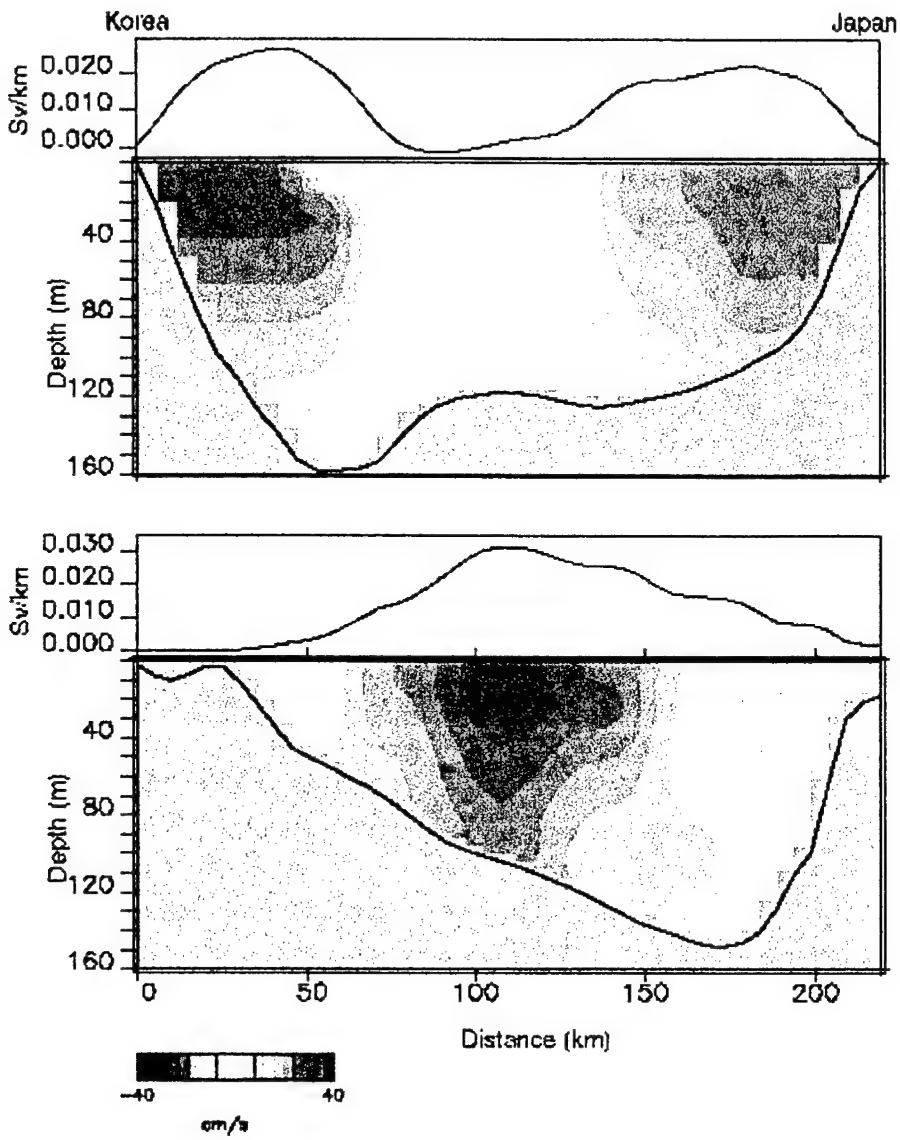


Plate 4. The mean velocity perpendicular to the north mooring line (top) and south mooring line (bottom) indicate the change in transport from the central portion of the strait at the inflow to the intensification near the coasts at the outflow. The counter current flowing from the East Sea to the east coast of Tsushima Island is apparent along the north section. The line plots indicate the vertically integrated velocity, which is transport per distance along the section.

Plate 5

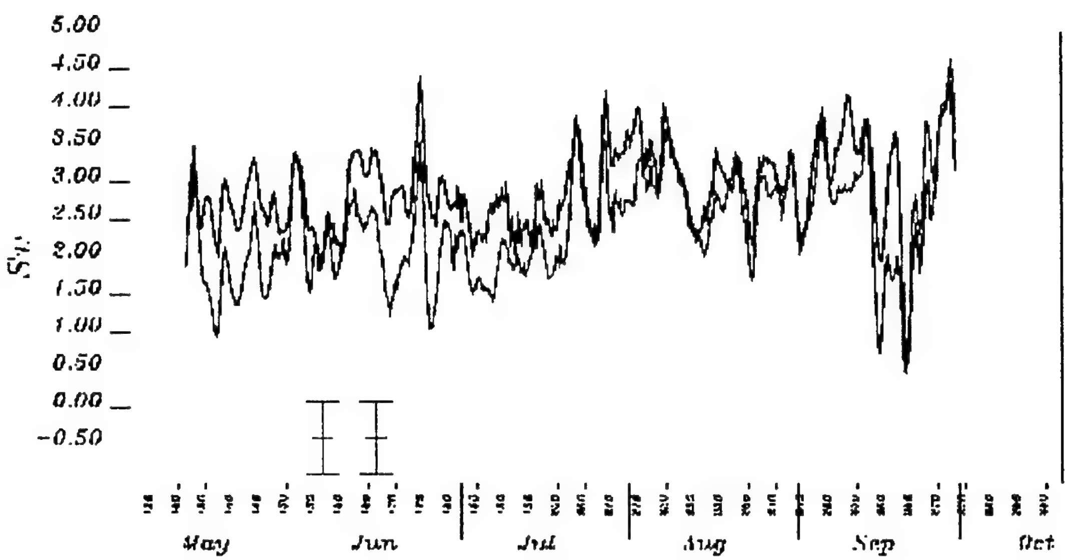


Plate 5. The transport estimated from the southern mooring line (blue) and the northern mooring line (red) indicate a time-averaged mean of 2.8 Sv and 2.4 Sv respectively. The RMS transport error estimate at any single time is shown in the lower left by the confidence intervals. These error estimates are time-invariant.

TIDES

Tides are analyzed in the Korea-Tsushima Strait using measurements from the 11 ADCPs and 11 pressure gauges. These instruments were bottom moored at depths ranging from 59 to 142 m. Tide amplitudes range over 3 m along the southern line but only range about 0.7 m along the northern line. Maximum total current velocities exceed 100 cm/s in the surface layers and typically exceed 50 cm/s at mid-depths along both lines. These data are analyzed for eight tidal constituents, which are found to account for about 88% of the sea surface height variability along the southern line and 70% along the northern line. M2, S2, K1, and O1 are the dominant constituents. Their amplitudes are generally 10-20% lower than amplitudes from tide charts. M2 tidal velocities range from 17 to 25 cm/s along the line northeastof Tsushima Island, and are largest at the mooring on the western side of the Strait, nearest to Korea. Southeast of Tsushima Island, either M2 or K1 dominates the tidal contribution to the current, with tidal velocities ranging between 13 to 23 cm/s. Tidal velocities are fairly depth independent at mid-depths but exhibit varying degrees of depth dependence in the near-surface and near-bottom layers. While tidal currents are responsible for about 25% of the eddy kinetic energy in the near surface layer, they account for more than 50% of the eddy kinetic energy at mid-depths and about 70% near the bottom.

Tidal Ellipses

Tidal ellipse parameters are calculated at each depth level. Current amplitudes corresponding to the ellipse major axes and ellipse local inclination angles for the four main constituents (M2, S2, K1, and O1) as a function of depth are shown. For an entirely barotropic tide the constituent amplitude and inclination angle would appear as vertical lines. The M2 current velocity is dominant along the northern section while either M2 or K1 is largest along the southern section. K1 tidal velocities peak between 25-40 m along the southern section and are dominant in the surface layer towards the eastern end. M2 velocities along the northern section are larger than along the southern section. The S2 current velocity is the smallest of the four components along the southern line while either S2 or O1 velocities are smallest along the northern section. Differing degrees of bottom and surface boundary effects are evident in each of the constituents. At mid depths, varying degrees of depth dependence are evident. Inclination angles shown have been offset for plotting purposes. The angle ranges are relevant while the absolute magnitudes are not. Vertical inclination angle gradients are largest near the surface and near the bottom. These large gradients imply decreasing velocities and turning of the tidal ellipses. At mid-depths, the ellipse turning is minimal, generally less than 10 degrees. Turning is most pronounced near the bottom. Veering with depth of the diurnal tide is opposite that of the semi-diurnal tide.

Tide Amplitudes as a Function of Depth Southern Line
Tide Amplitudes as a Function of Depth Northern Line

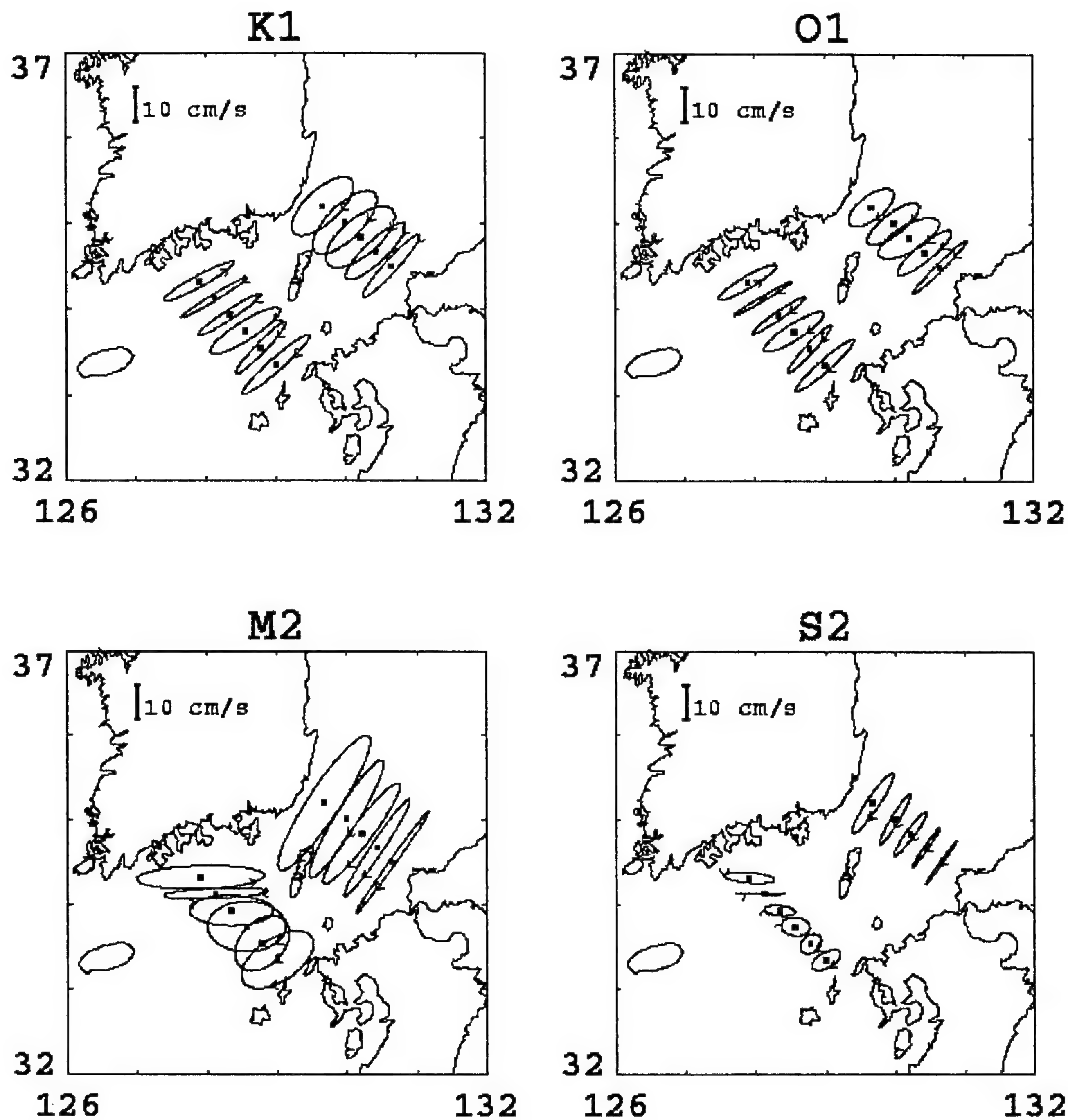
The contribution of tidal currents to the total velocity field generally increases with depth, with some exceptions in the bottom boundary layers. Tides contribute more to the total velocity field along the northern section than along the southern section. Tides contribute the least towards the total current at S3 and S4 which usually coincide with the core of the Tsushima Current. Tides contribute the most towards the total current at the ends of the southern section (S1 and S6). Along the northern section, tidal currents are most dominant at N3 and N4, located in the regime of highly variable flow with a weak mean flow. Tidal effects are noticeably smaller in the near bottom layer at N2, where significant

southward influx of bottom cold water has been observed.

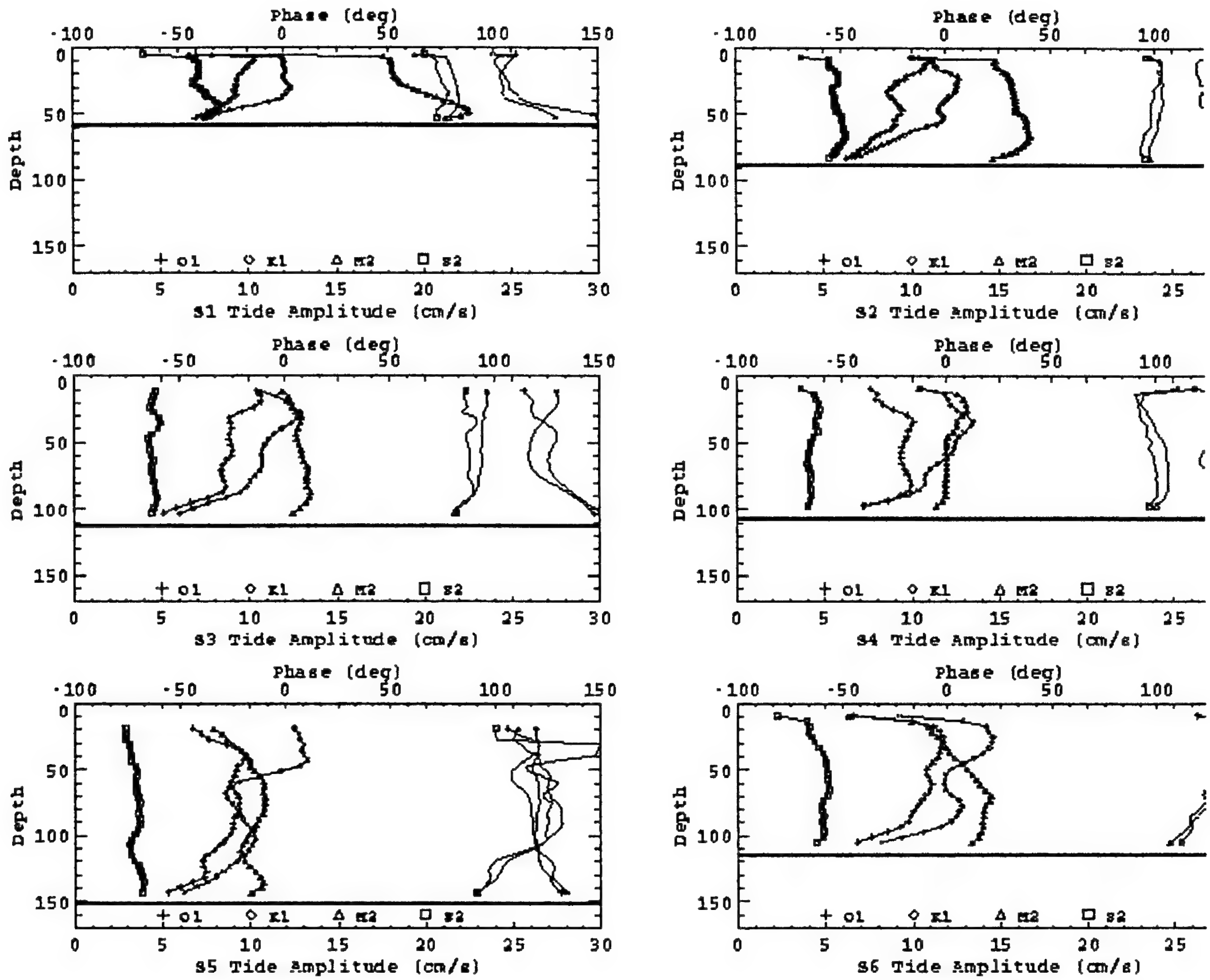
Ratio - Tide MKE/Total MKE
Ratio - Tide EKE/Total EKE

Tide chart tidal amplitudes (cm) and Greenwich phases (squares) from Odamaki (1989, Journal of the Oceanographic Society of Japan, 45, 65-82) are compared with computed amplitudes and phases (asterisks) from pressure gauge moorings deployed along lines northeast (N2--N6) and southwest (S1-S6) of Tsushima Island.

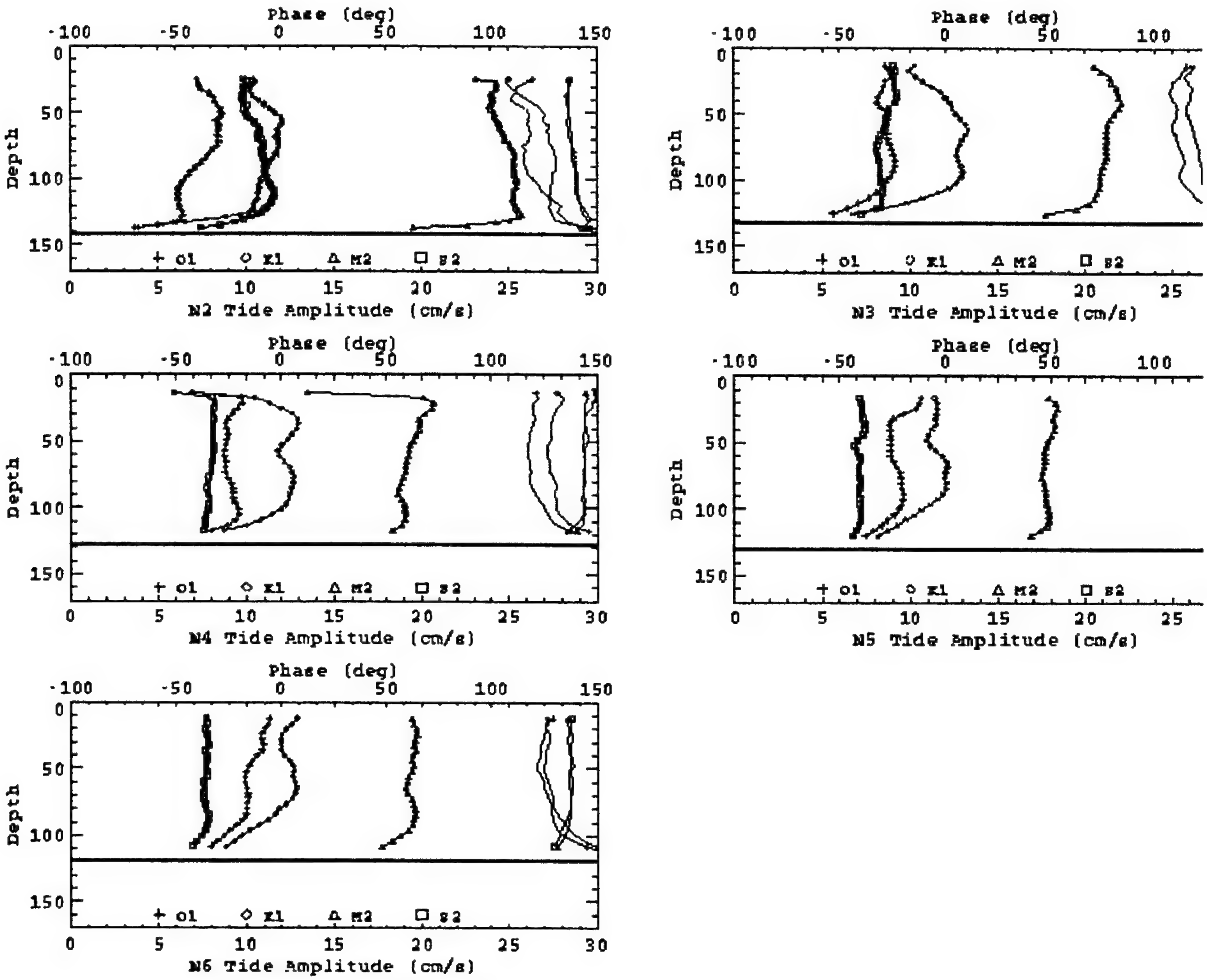
Tide Amplitudes and Phases compared with Charted Values



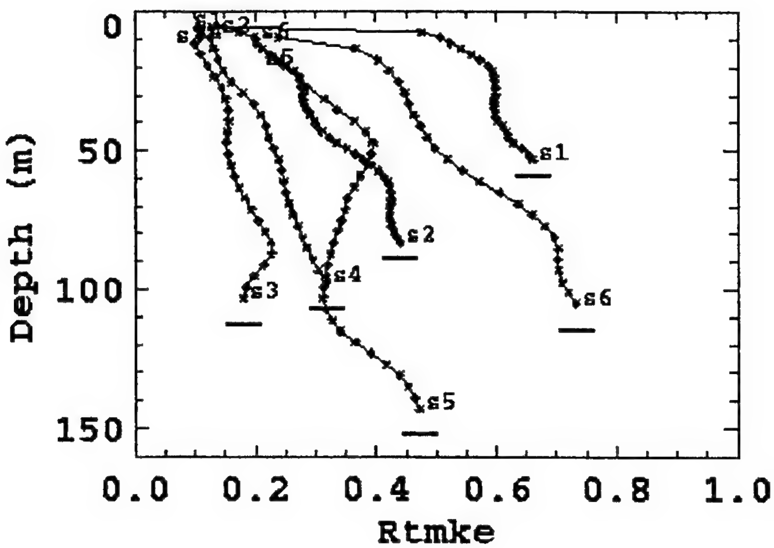
Current ellipses with sense of rotation arrows. Note the different velocity scales in the upper left corner in each panel.

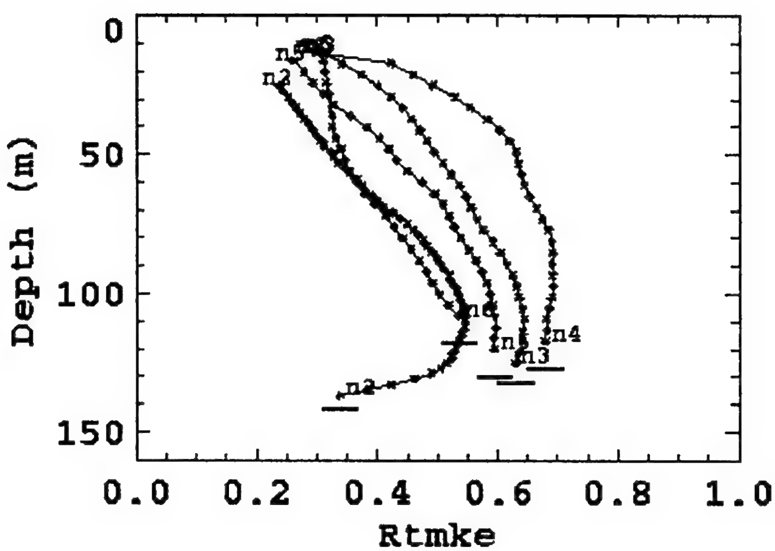


Amplitudes of the individual tidal constituents (M2, S2, K1, and O1) correspondi to the magnitudes of the major axes of the tidal ellipses for the southern line. E computed tidal velocity is marked by an identifying symbol. Corresponding loca inclination angles are given by the thin lines marked by symbols at the ends. Tl bold horizontal line indicates bottom depth.

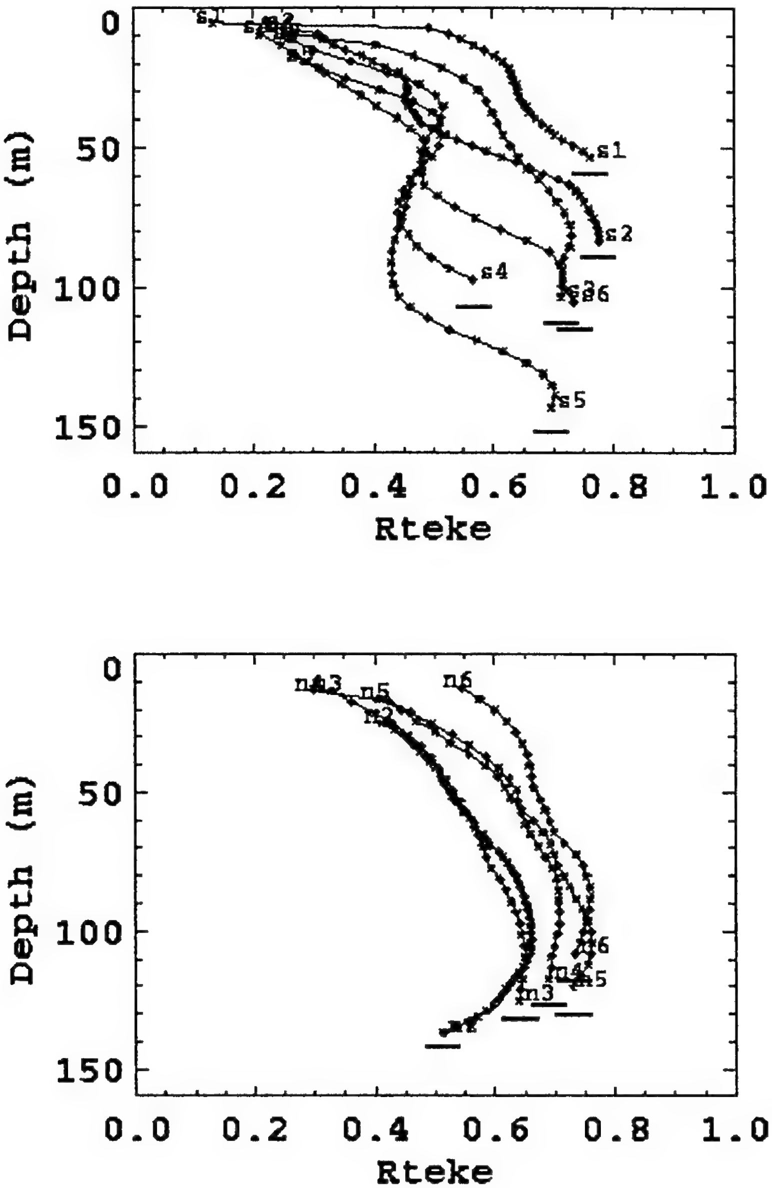


Amplitudes of the individual tidal constituents (M2, S2, K1, and O1) correspondir to the magnitudes of the major axes of the tidal ellipses for the northern line. Ea computed tidal velocity is marked by an identifying symbol. Corresponding local inclination angles are given by the thin lines marked by symbols at the ends. Th bold horizontal line indicates bottom depth.

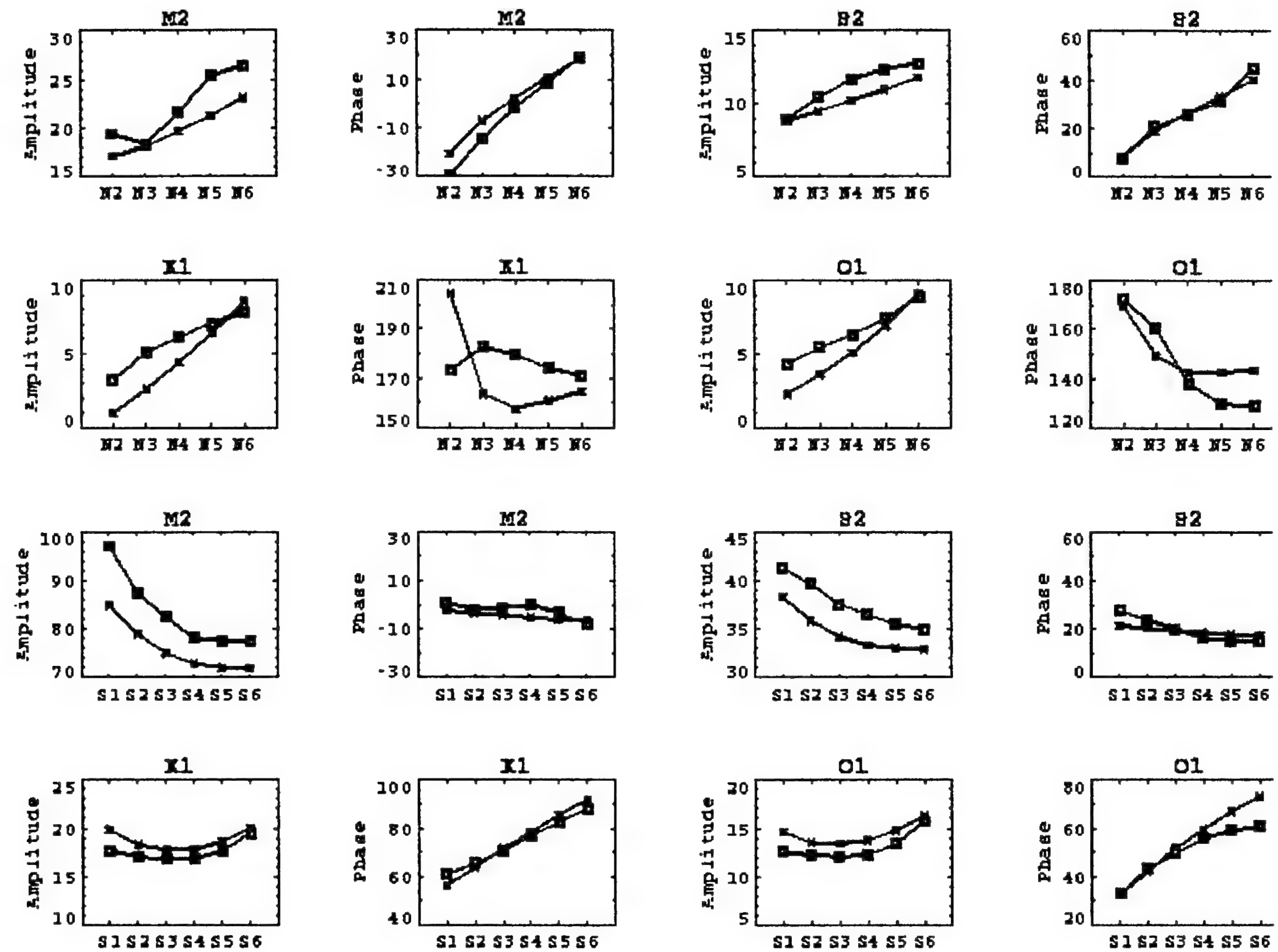




Contribution of tidal currents to the total mean kinetic energy Rtmke.



Contribution of tidal currents to the total eddy kinetic energy, Rteke.



Tide chart tidal amplitudes (cm) and Greenwich phases (squares) from (Odamaki, et al. 19 are compared with computed amplitudes and phases (asterisks) from pressure gauge moor deployed along lines northeast (N2--N6) and southwest (S1--S6) of Tsushima Island.

INERTIAL CURRENTS

Inertial Oscillations (IOs) are examined. Results indicate strong IO response to wind events during summer. In spite of winter wind events that are equivalent in magnitude and more numerous than those in summer, the winter IO response is very weak. During summer, the currents within the mixed layer and below the mixed layer are of comparable amplitude and in opposite directions. The depth at which the currents reverse directions varies through the year as the mixed layer deepens from about 40 m during summer to the bottom of the water column in November. During winter, the vertical velocity structure is more uniform with currents in the same direction throughout the water column. One possible explanation for these phenomena is the combination of the strait boundaries and the strong summer stratification. The stratification prevents the wind stress momentum flux from mixing downward below the thermocline and thus allows the development of a bottom current separate from the surface current. Such a velocity structure is necessary to satisfy the no flow condition through the land boundaries. Thus, the stratification aids in developing the oppositely directed currents in the surface and below the mixed layer. The uniform winter stratification does not allow such a vertical velocity structure to develop as easily. The wind stress momentum flux is able to mix vertically downward to the bottom, and land boundaries prevent vertically uniform inertial oscillations.

Mooring Locations

Rotary Spectra

Extended EOF Analysis - Mode 1

Extended EOF Analysis - Mode 2

Wind Stress

Wind Stress Curl

Mean Temperatures

Negative Rotary Spectra (3-Day Window)

Positive Rotary Spectra (3-Day Window)

Amplitude Spectra (20 Day Window)

Amplitude Spectra (3 Day Window)

Negative Rotary Spectra (20-Day Window)

Figure 1

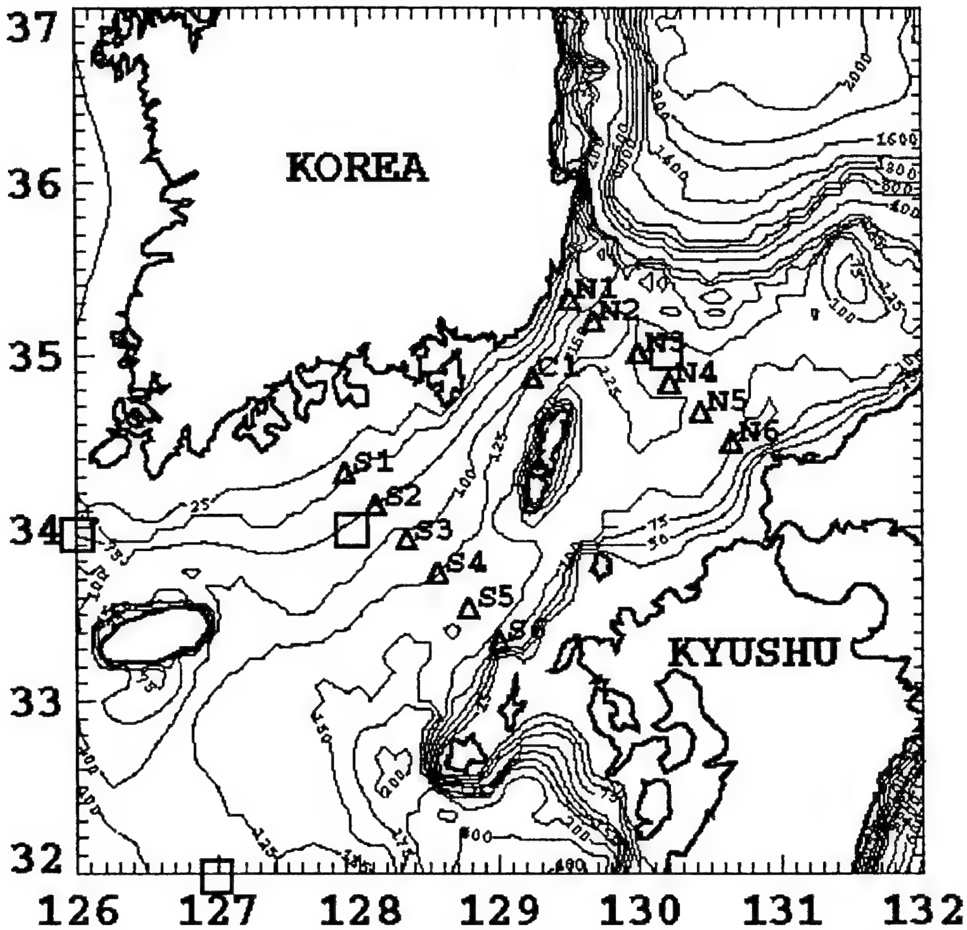


Figure 1. The Acoustic Doppler Current Profiler (ADCP) moorings are deployed along two lines, northeast (N1 through N6) and southwest (S1 through S6) of Tsushima Island and in the narrow between the Korea peninsula and Tsushima Island (C1), from May 1999 through March 2000. The 4 squares are points at which the wind stress is examined (Figure 4 and Figure 5).

Figure 2

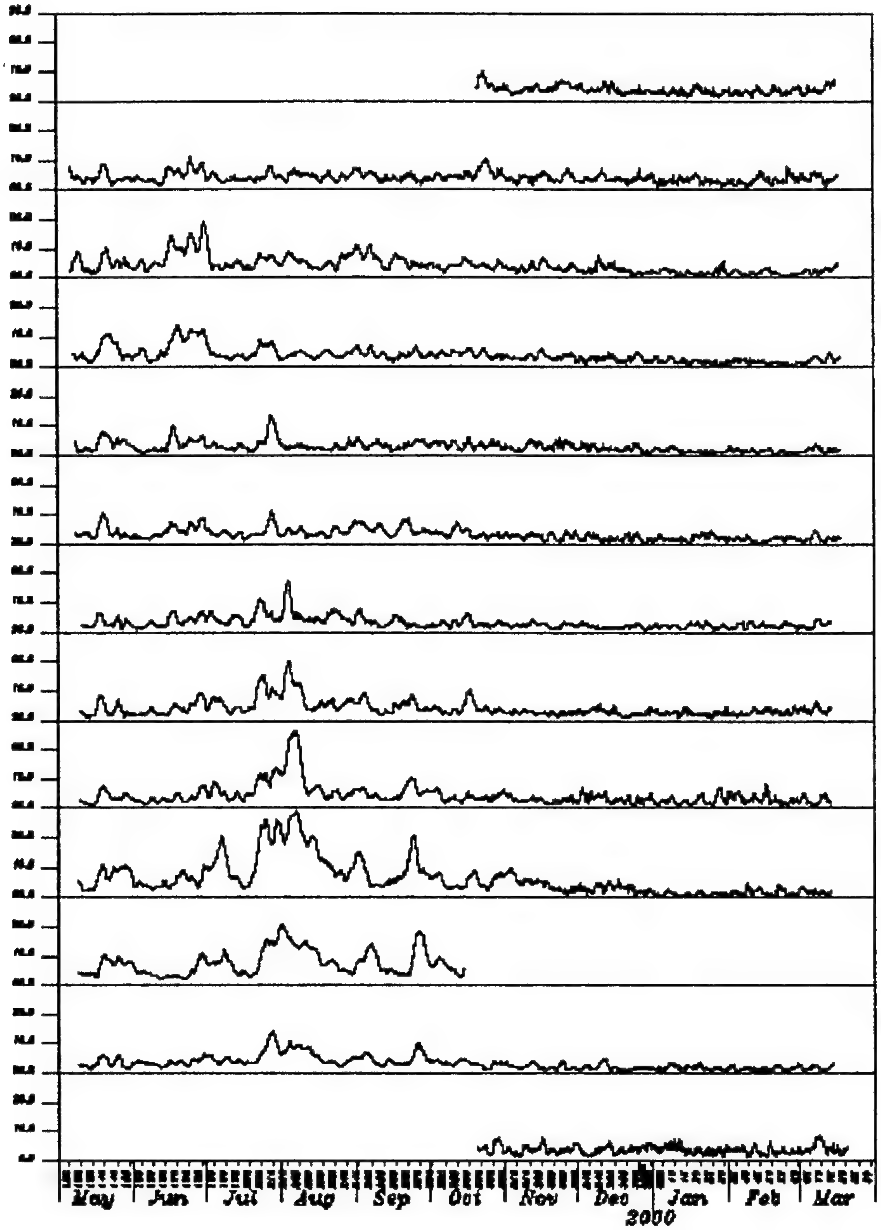


Figure 2. The vertically averaged amplitude of the negative rotary spectra at only the inertial frequency for the 13 ADCP moorings indicates the main events occur in May through September. Very little variability occurs at the inertial frequency during winter. The variability in the southern line during July/August is correlated to the passage of a typhoon event traveling northeast and passing across Kyushu (see wind stress curl in Figure 6).

Figure 3

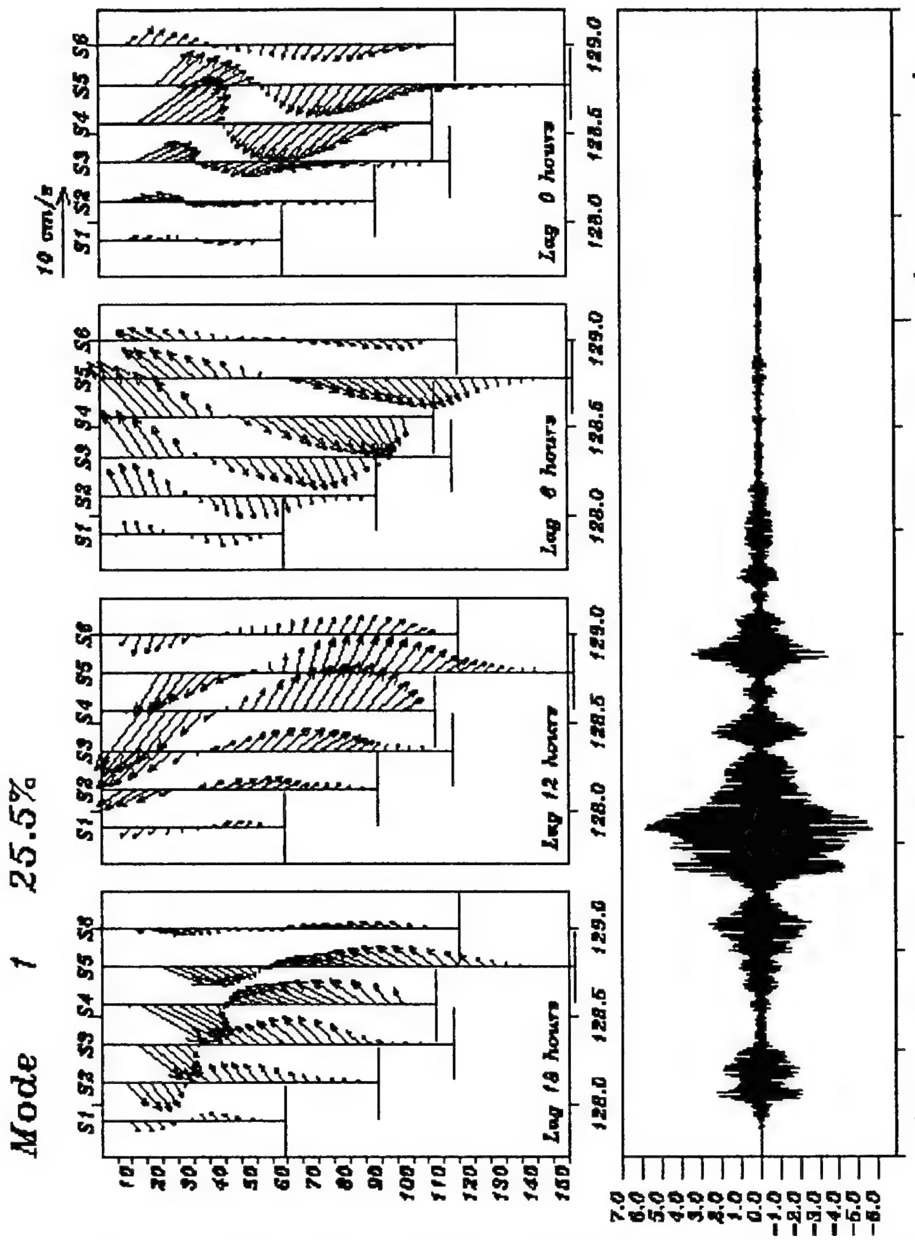


Figure 3. An extended eof using 4 lagged data sets from 18 to 0 hour lags indicates the temporal development at the southern moorings of the most correlated variability in space (horizontal and vertical) and time. This is based on the variability at only the inertial frequency, so the clockwise rotation of currents is apparent. The time series indicates when this type of development occurs (mainly summer). The currents at a particular time are obtained by multiplying the amplitude of the time series by the spatial amplitude. Thus, peak currents reach 60 cm/s. At time lag 12, surface currents are directed towards Korea, and at time lag 0, surface currents are directed toward Japan.

Figure 4

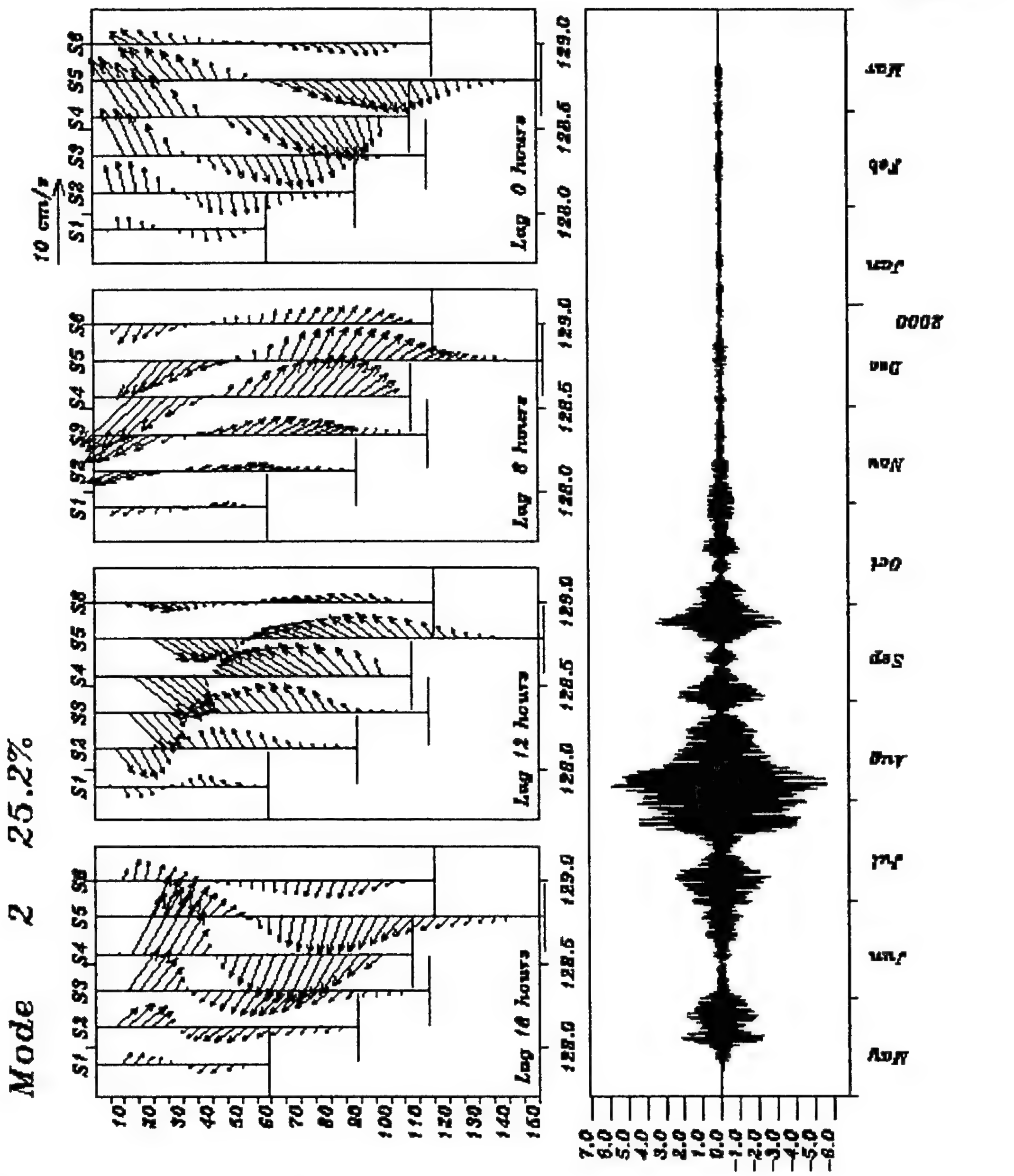


Figure 4. The same as Figure 3, except for the second extended eof mode. This is based on the variability at only the inertial frequency, so the clockwise rotation of currents is apparent. Together, the first and second modes explain 50% of the variability at the inertial frequency. These two modes form the equivalent of the cosine and sine coefficients of a time series. The next two modes each explain 4.5% of the variability.

Figure 5

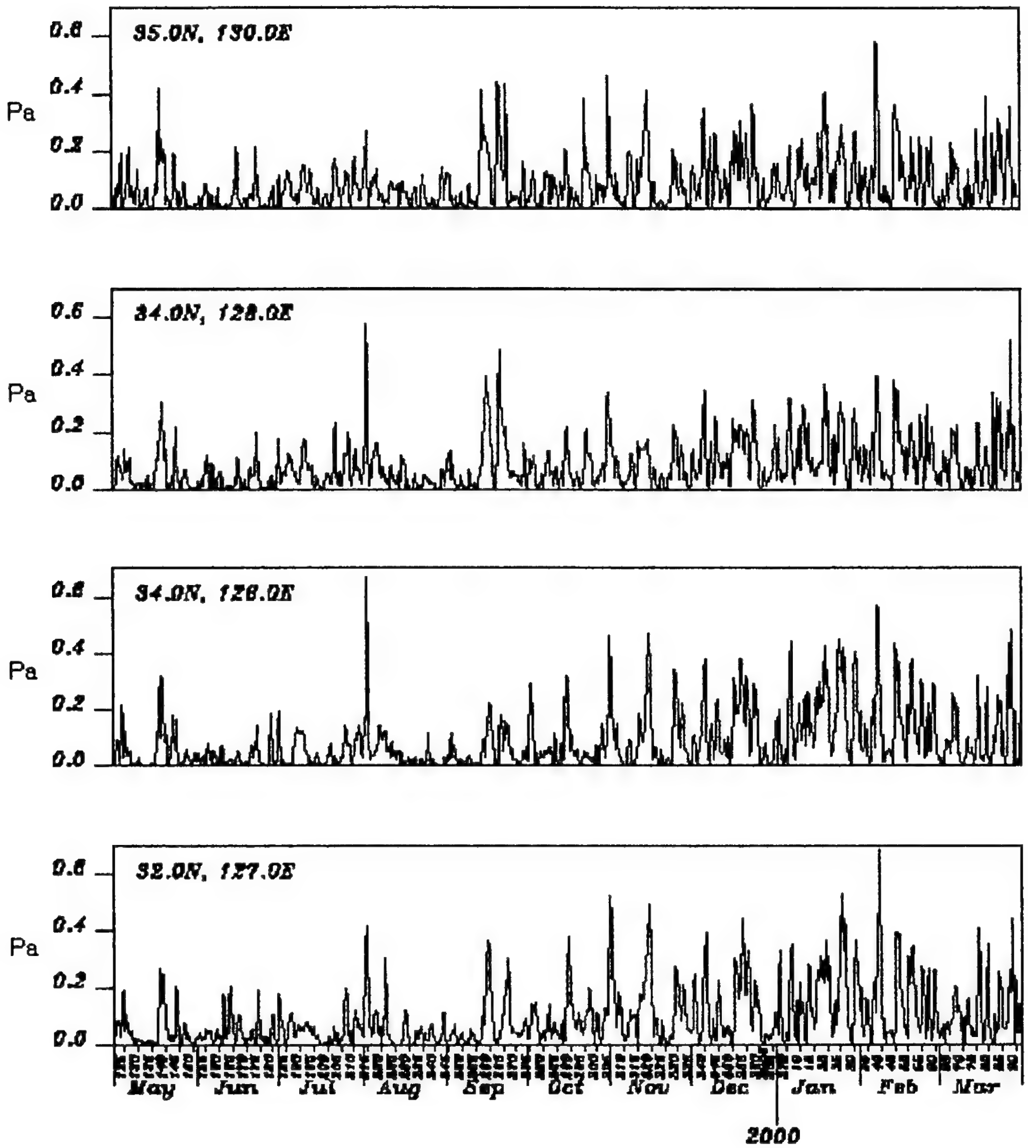


Figure 5. Wind stress magnitude at 4 points surrounding the Korea Strait (see Figure 1 for positions) indicate events during May and July/August that correlate with the intertial oscillation amplitude. However, the increased events of the same amplitude during winter do not appear to generate inertial oscillations.

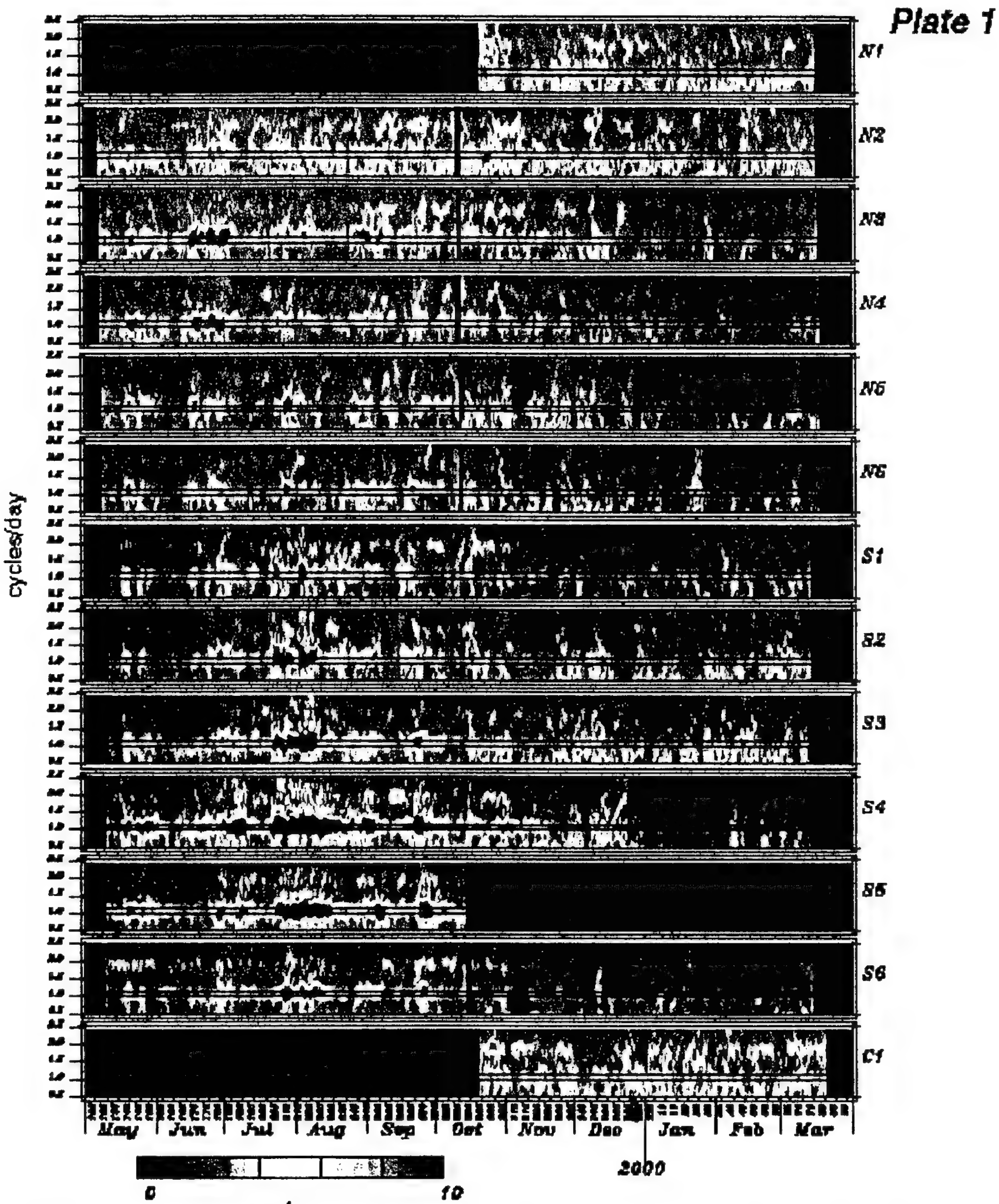


Plate 1. The negative rotary spectra is computed using 3 day's of data centered at each point in time. The spectra at all depths are averaged together for each mooring. The 3 day window provides a good indication of when inertial oscillation events occur. A longer 20 day window provides an indication of the frequency of the events (Plate 3). The two horizontal lines in each plot are at the 1 cpd and 1.15 cpd frequencies.

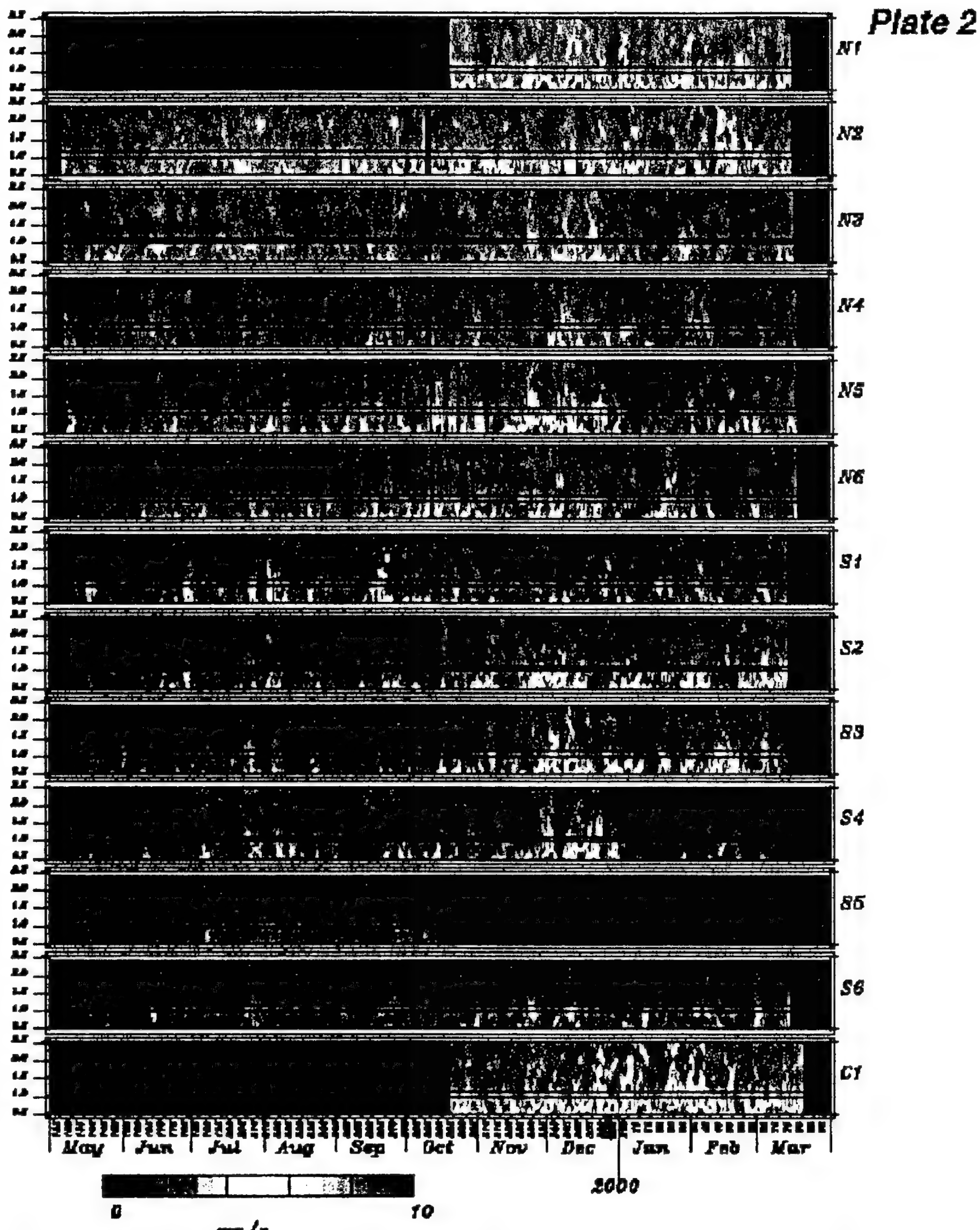


Plate 2. The positive rotary spectra is computed using 3 day's of data centered at each point in time. The spectra at all depths are averaged together for each mooring. Comparison with the negative rotary spectra (Plate 1) indicates that the summer is strongly dominated by clockwise-rotating currents while the winter indicates only minor events during which the clockwise-rotating velocity is larger than the counterclockwise-rotating velocity.

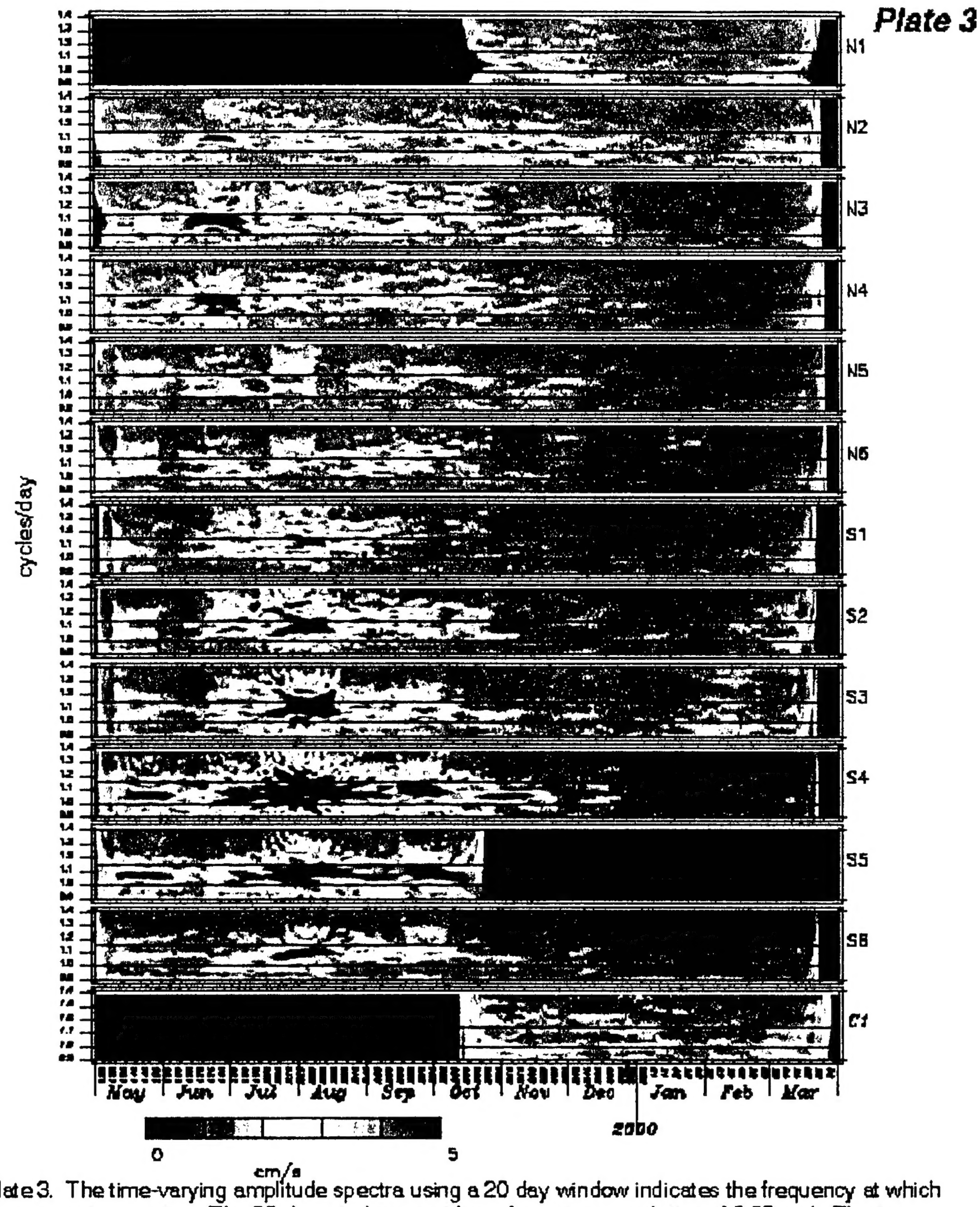


Plate 3. The time-varying amplitude spectra using a 20 day window indicates the frequency at which the energy is occuring. The 20 day window provides a frequency resolution of 0.05 cpd. The two horizontal lines in each plot are at the 1 cpd and 1.15 cpd frequencies. Most of the energy is at a frequency slightly less than the inertial.

Plate 4

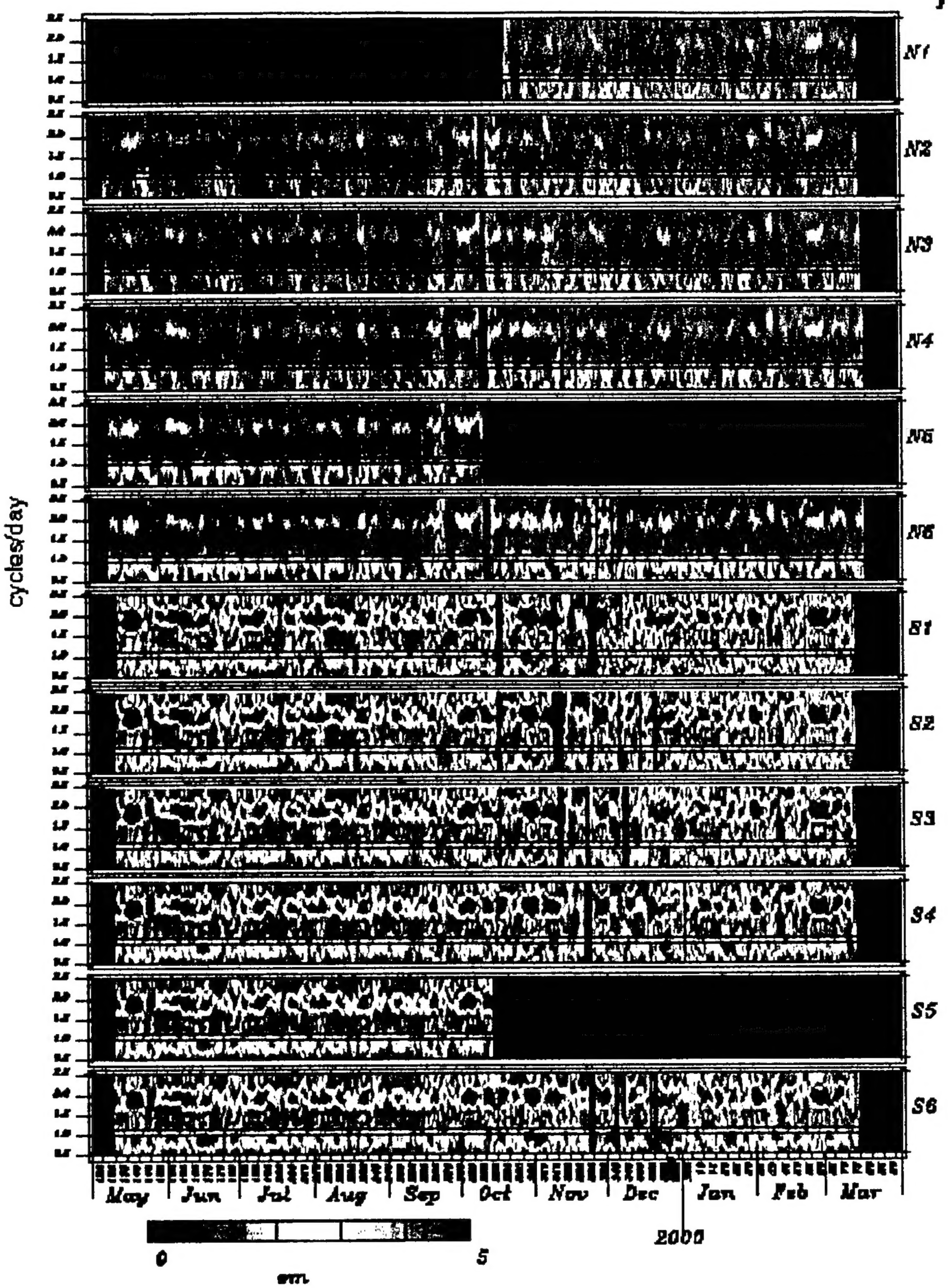


Plate 4. The time-varying amplitude spectra using a 3day window of the pressure gauge data (pressure is converted into sea surface heights) indicates strong residual tidal energy just below 1 cpd and 2 cpd. This is in contrast to the velocity spectra that are relatively free from tidal energy after removing only 8 constituents. The pressure spectra do not indicate any anomalous variability during the times when inertial oscillations appear in the velocity records (particularly in March and July/August). Mooring C1 did not contain a pressure gauge.

Plate 5

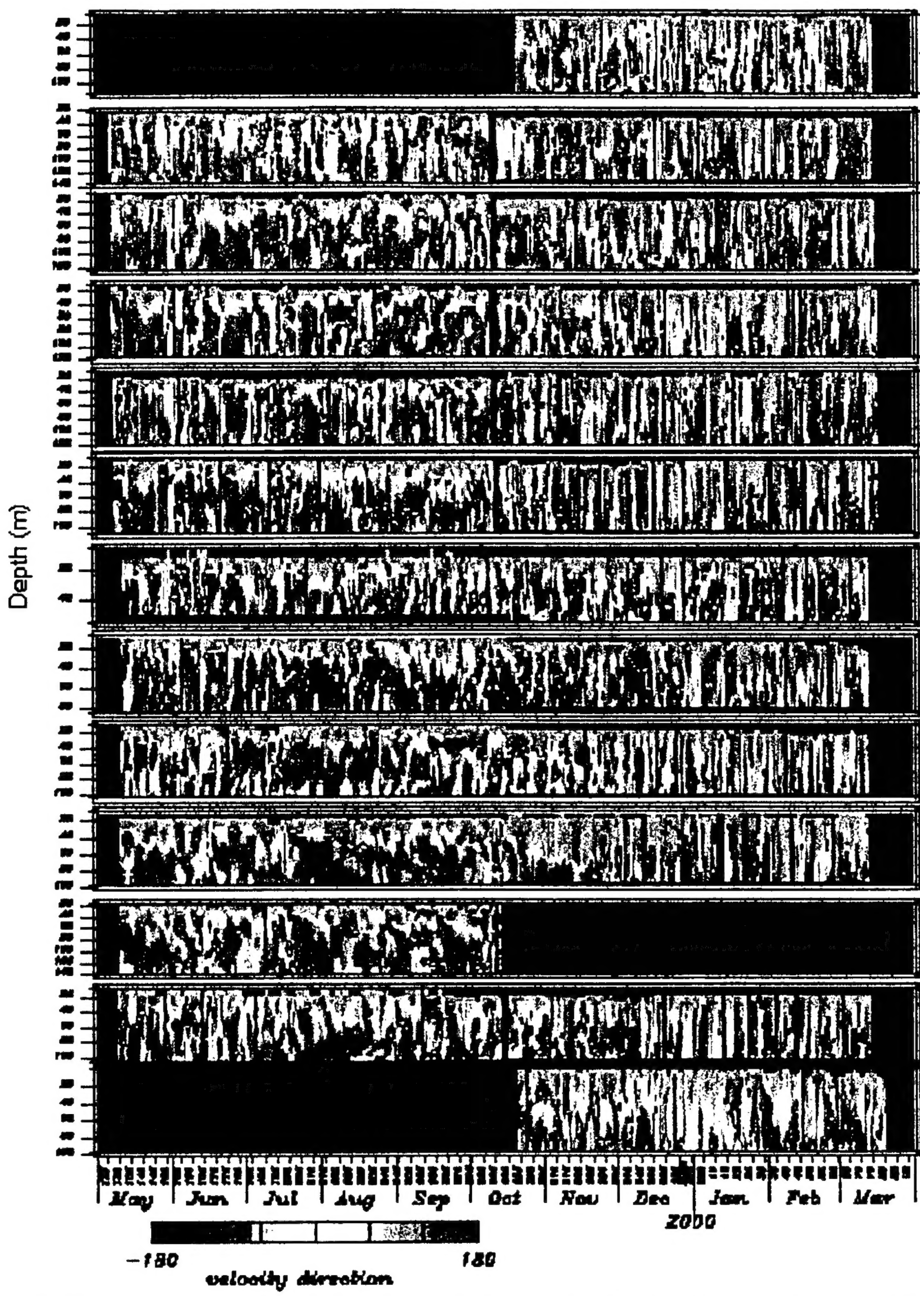


Plate 5. The negative rotaray spectra using a 3 day window (Plate 1) are used to examine the relative phase throughout the water column. The surface currents at each time are rotated to 90 degrees (eastward), and all other currents are rotated by the same amount. In summer, particularly along the southern moorings, the current direction within the mixed layer (about 90) is in the opposite direction of the currents below the mixed layer (about -90). During October through November, the level at which currents change directions deepens. The direction reversal is also apparent in the extended eof analysis (Figure 3 and Figure 4).

More details of the work presented here will soon be available in journal articles. Papers submitted thus far include:

Perkins, H.T., W.J. Teague, G.A. Jacobs, K.I. Chang, and M.-S. Suk, Currents in Korea-Tsushima Strait during summer 1999, submitted to Geophys. Res. Let., 1/00.

Jacobs, G.A., H.T. Perkins, W.J. Teague, and P.J. Hogan, SummerTransport Through the Korea-Tsushima Strait, submitted to J. Geophys. Res., 2/00.

Teague, W.J., H.T. Perkins, G.A. Jacobs, and J.W. Book, Tide Observations in the Korea-Tsushima Strait, submitted to Cont. Shelf Res., 4/00.

Jacobs, G.A., J. Book, H.T. Perkins, W.J. Teague, Inertial oscillations in the Korea Strait, submitted to J. Geophys. Res., 6/00.